SPATIAL ANALYSIS OF CHANNEL STEEPNESS IN A TECTONICALLY ACTIVE REGION: PUTNA RIVER CATCHMENT (SOUTH-EASTERN CARPATHIANS)

Alexandru - IonuţCRISTEA[1]

ABSTRACT:
Landforms in the PutnaRiver catchment are the result of a recent tectonic evolution, starting with Early Pleistocene. The longitudinal profiles of the rivers draining the region are expected to reflect, in terms of channel steepness, the influence of tectonic distortions and were further analyzed using a locally determined steepness index. This was derived from a power law fit between upstream area and local channel gradient, extracted from the study area's DEM. Because other factors than tectonics can determine high steepness values (e.g. lithology), a spatial analysis have been conducted. This indicated that the rock variability hardly explains the hot spots and the rivers are steeper more likely in two north-south oriented narrow strips near the major front thrusts. In order to identify clusters in data values local indices of spatial autocorrelation (LISA, GetisOrdGi*) have been used. The results confirm that a probably a tectonically induced signal can be noticed at a medium scale (where rock strength influence fails to explain data clustering), though at higher (local) scale other factors such as lithology and mass wasting processes can have stronger influences.

Key-words: *Active tectonics, Channel steepness, Spatial autocorrelation, SE Carpathians.*

1. INTRODUCTION

Among the geomorphic indicators, stream longitudinal profiles are considered to be the most sensitive to the regional tectonic uplift rates (Holbrook &Schumm, 1999, Burbank & Anderson, 2001). Additionally stream incision rates in bedrock are influenced by the climatic oscillations, rock strength or by the characteristics of the alluvial deposits (Duvall, Kirby & Burbank,2004). The shape of the profile can indicate therefore consistent evolutionary aspects of the river valleys and the main role in this general framework is played by the identification and interpretation of the oversteepenedstream reaches.

Stream profile analysis frequently envisages the establishment of mathematical relationships of channel parameters (mostly using power functions), ideal at steady-state equilibrium (SSE). In case of fluvial systems and of the mature rivers at SSE, channel bed elevation will be stable (uplift and erosion are equal) and the longitudinal profile will be smooth and concave up(Hack, 1973). This implies certain relations between local stream gradient and stream length (Hack, 1957) or between local channel steepness and upstream drainage area (Flint, 1974). At SSE, the local channel gradient of a stream will reduce as a power law function because of a larger catchment. Consequently inconsistent relationship between channel gradient and upstream drainage area can be related to local disequilibrium and can be further associated with active tectonics, base level falls, changes in lithology or stream discharge.

The current paper aims to investigate the distribution of the oversteepened stream reaches in a well-known tectonically active area in Europe – South-Eastern Carpathians

[1]*Ştefan cel Mare University of Suceava, 720229 Suceava, Romania,icristea@atlas.usv.ro.*

(Romania) and to draw conclusions about the influence of the Quaternary tectonic activity on the fluvial system.

2. **REGIONAL SETTINGS**

South-Eastern Carpathians (VranceaRegion) received an increasing scientific attention during the past years. Among the relevant topics on this area we can mention the detailed reconstruction of the tectonic chronology of the region during the Neogene - Quaternary period (Maţenco et al, 2003; Bertotti,Maţenco&Cloetingh, 2003; Tărăpoancă et al., 2003; Maţenco et al., 2007; Necea, Fielitz&Maţenco,2005; Merten, 2011), the assessment of the uplift / subsidence rates and their influence on the landscape (van der Hoeven et al., 2005; Cloetingh et al., 2005; Fielitz&Seghedi, 2005; Necea, 2010). According to Merten (2011)the region conserves the youngest topography in the Romanian Carpathians resulting froma building (deformational) process occurring during the late Pliocene – Pleistocene.Moreover, the tectonic activity continues to the present (Holocene) as it is confirmed by the geodetic measurements(up to 4 mmy^{-1}uplift in the Carpathians anddown to –3 mm y^{-1}subsidence in the northern part of the Romanian Plain - van der Hoeven et. al., 2005) or by the frequency of crustal earthquakes. The specific effects of the Quaternary deformations on the fluvial system were associated with increased incision and the formation of the degradational (strath) terraces, downstream tiling of terraces (Necea, Fielitz&Maţenco, 2005), the creation of local drainage divides (Fielitz&Seghedi, 2005) and young longitudinal river profiles (Rădoane, Rădoane&Dumitriu, 2003).

Situated in the northern part of the region, PutnaRiver drains a rather complex landscape with elevations decreasing gradually eastward - from 1500 m to less than 15 m at the confluence with Siret, in the Romanian Plain. Similar with other rivers in the area, it is oriented nearly transversal to the strikes of the Eastern Carpathians nappes (Tarcău and Marginal Folds) and those of the Foreland'sstructures.This study focuses on the upper part of its catchment (**Fig. 1**, A) which overlaps the folded structures of the eastern flank of Vrancea Mountains and the internal part of the SubcarpathianHills, downstream to the ValeaSării village (c. 1054 km^2).

Sedimentary formations in the mountain area consist of flysch sequences (conglomerates, sandstones, limestones, marls and claystones) of Paleogene andCretacious ages. The exposure of the Lower Cretaceous sediments in the Vrancea half-window (Marginal Folds) was associated with the presence of the reverse faults in the Moesian basement and with an accelerated uplift in the late Early Pleistocene (Necea, 2010). The western (internal) part of the Foreland (Subcarpathian nappe)is composed of folded molasse-type deposits (sandstones, conglomerates, marls and claystones) with Miocene age.

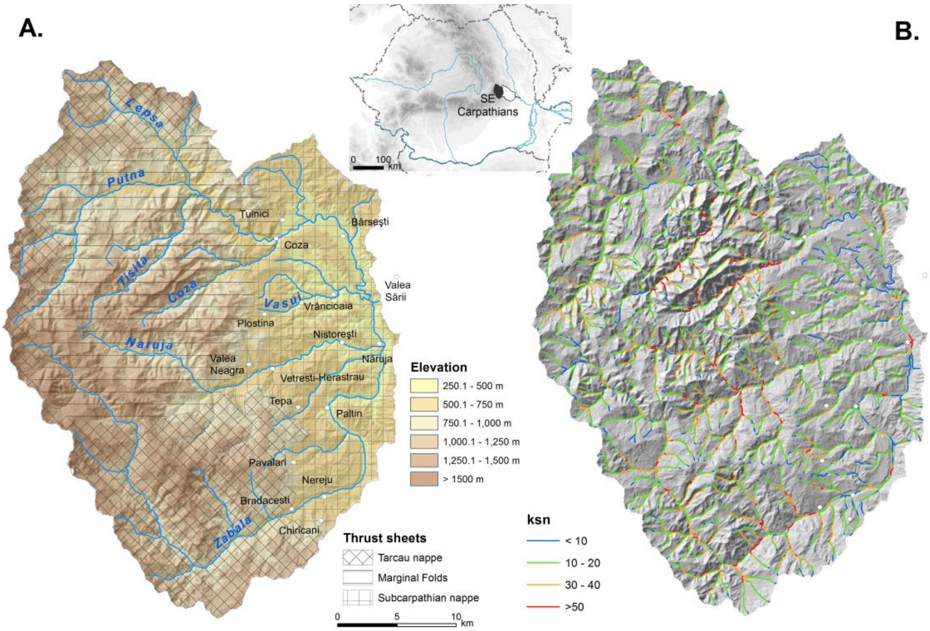


Fig. 1 Study area – the upper part of the PutnaRiver catchment: A. Elevation and main geological units; B. Distribution of the normalized channel steepness index.

Drainage network in the region consistently reflects this lithological complexity and recent tectonic evolution. Rivers are deeply incised into bedrock up to 250 meters, have significant knickpoints and rapids, such is Putna when crossing the Marginal Folds. Nevertheless the presence of some equally importance tributaries coming from Carpathians - Nărujaand Zăbala rivers, and the increased resistance in the Subcarpathian nappe frontal thrust determined a specific pitchfork drainage pattern for the study area, similar to the one identified by Gupta (1993) at the contact between the Lower Himalayas and the Siwalik Hills.

3. METHODS

The methodology used for the evaluation of the stream profiles in the study area is based on the Flint's empirical power-law equation that relates the local slope (S) to the upstream contributing drainage basin area (A):

$$S = k_s A^{-\theta} \tag{1}$$

where k_s is a steepness index and θ is the stream concavity. Increases in the k_s values can be related to the presence of anomalous uplift rates or a more general reduce in the erosional efficiency (Snyder et al., 2000; Kirby & Whipple, 2001;Vanlaningham, Meigs&Goldfinger, 2006). For the same upstream area the slope of a channel experiencing a high uplift rate is higher than the slope of a channel experiencing low uplift rate. Concavity is an indicator of the distribution of the elevations along stream profile and it is empirically considered to range between 0.35 and 0.6 (Wobus et al., 2006). The equation is basically a stream power incision model (Lague, 2014) and is ideal for the steady-state bedrock channels with uniform geology. For the transitory states, spatial or temporal variations in rock uplift rate or non-uniform rock strength, sharp changes in slope and slope-area ratio will occur along the profile.

In order to identify and further analyze the geographical distribution of the atypical channel reaches in a broader context (study area), a two-stage method was established. In the first, θ and k_s are computed for successive stream segments using equation (1) as the regression model. In the second a normalized steepness index is determined for the individual segments using a reference concavity (θ_{ref}):

$$k_{sn} = k_s A_{cent}^{(\theta ref - \theta)} \tag{2}$$

where$k_s$and θ are determined by regression for each stream segment, $A_{cent}$is the drainage upstream area in the segment's midpoint and θ_{ref}– a given reference concavity (e.g. 0.45). This is required in the interpretation of data due to the strong correlation between concavity (regression slope) and steepness index (regression intercept) and the highly variable upstream drainage areas (Wobus et al., 2006). In practice, θ_{ref} is considered to be the regional mean of observed concavity values.Duvall, Kirby and Burbank(2004) indicated that, in relative terms, k_{sn} values are however independent of the chosen reference concavity.

For the Putna upstream catchment area channel profiles were extracted from a 25 m DEM. This was generated in ArcGIS 10.1 from the elevation points, 20 m contours and stream coverage available on the 1:50.000 topographical maps, using ANUDEM gridding procedure. Slope-area regression analysis was performed using ArcGIS and Matlab software packages (Whipple et al, 2007) according with the methodology and the specific tools developed by Snyder et al. (2000) and Kirby & Whipple (2003). The sampling interval considered was 20 m, in agreement with the original contour data. Reference concavity used for the steepness index normalization was established based on a preliminary profile analysis of the main rivers (Strahler order ≥5). Their concavity was found to range between 0.33 (Zabala, R^2=0.73) to 0.43 (Putna, R^2=0.92), therefore a mean value of 0.37 was eventually used.

Spatial analysis of the obtained k_{sn} values (data clustering) was made using local indices of spatial autocorrelation (LISA) and GetisOrdGi* statistics. First is a modified Moran's I procedure used for the identification of local spatial clustering around "hot spots" (Anselin, 1995). The latter (Ord&Getis, 1995) compares the local values within a distance with the global ones. Gi* will be positive where higher values cluster and low (negative) in the opposite case. Both methods calculate for each feature's a specific Z-score and associated statistical significance (p-value). In this research, for p=0.05 results were considered significant.

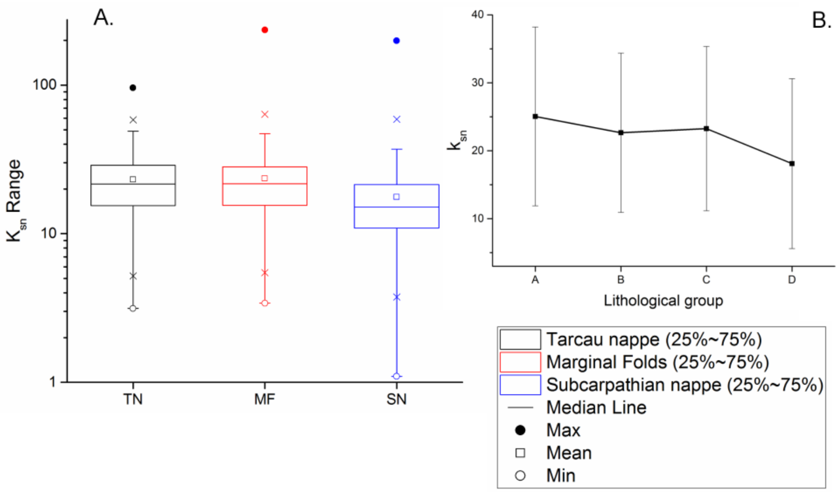
4. RESULTS

Geographical distribution of the k_{sn} values in the study area is presented in **Fig. 1**, B. Statistically one can note that the channel segments crossing the Flysch formations have rather similarsteepness values but these are more variable in the Marginal Folds domain.

Here also the maximum values are recorded (**Fig. 2**, A). In the Subcarpathian nappe values decrease although several reaches with increased steepness can be noticed.

Table 1. Main lithological groups in the study area, based on the potential erodability (Ichim et al., 1998) and the characteristic k_{sn}values.

ID	Lithological group	Relative resistance index	Mean k_{sn}	Min k_{sn}	Max k_{sn}	SD
A	Cretaceous (Senonian) complex	1.39	25.05	3.76	130.57	13.15
B	Group of Tarcau Sandstone	1.66	22.66	3.14	119.95	11.72
C	Group of Kliwa Sandstone	1.5	23.25	3.41	234.62	12.08
D	Molassic rocks	1	18.11	1.10	198.94	12.50



UNIT	N total	MEAN	SD	MINIMUM	MEDIAN	MAXIMUM
Tarcau nappe	2473.00	23.13	11.12	3.14	21.56	95.81
Marginal Folds	3329.00	23.48	13.09	3.41	21.69	234.62
Subcarpathian nappe	2178.00	17.62	12.43	1.10	15.12	198.94

Fig. 2 Descriptive statistics of the normalized steepness index values for: A. the main thrust sheets and B. main lithological groups (according to Ichim et al., 1998) – mean values and error bars (standard deviation).

Based on the 1:100.000 geologic maps, in the regional nappe system, 25 lithological formations can be identified. According with Ichim et al. (1998) these can be further classified based on their potential erodibility in four major groups (**Table 1**). For the stream segments intersecting each of these mean, minimum, maximum and standard deviation of the normalized steepness values have been summarized. In case of the lithological groups B, C and D, the mean k_{sn} presents a positive correlation with the rock types. Surprisingly the mean value is highest in the A group, considered to be less resistant to erosion than C and B (**Fig. 2**, B). Certain correlations within data are however difficult to sustain due to the high standard deviations (error bars). Therefore the influence of lithology is not enough to explain the large variations of the stream steepness.

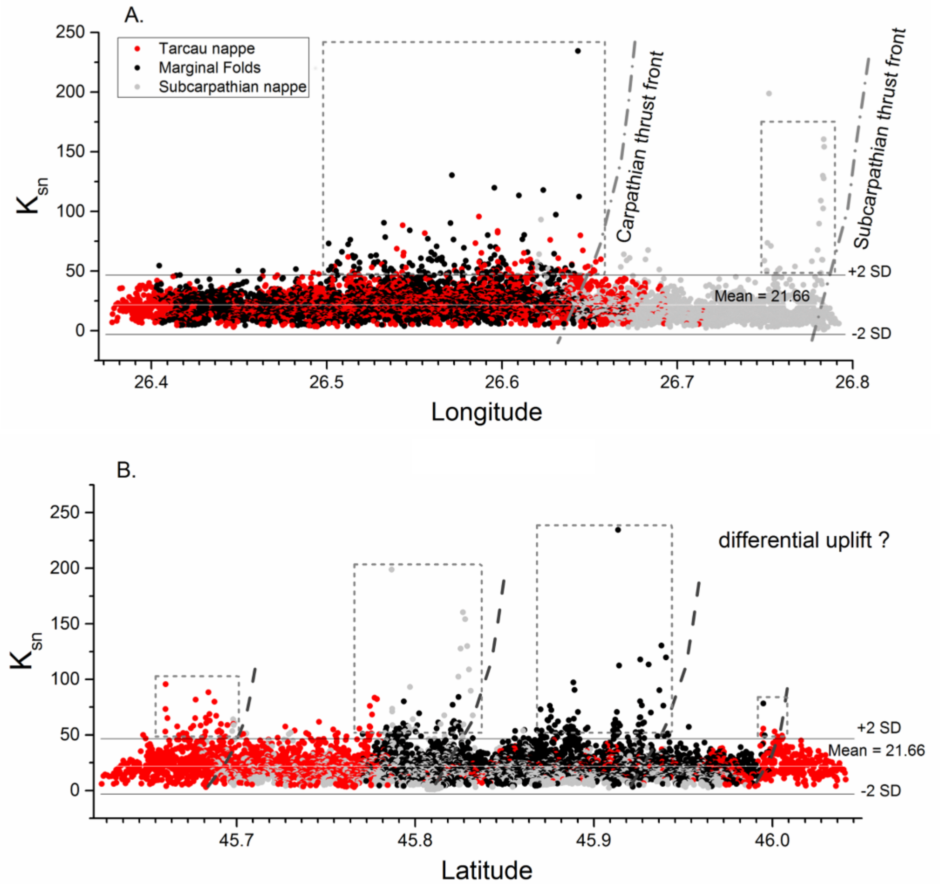


Fig. 3 Distribution of ksn values by geographic coordinates.

A more detailed spatial analysis indicates that the major increases in the normalized steepness index tend to longitudinally group between 26.5° – 26.66° E and 26.75 ° - 26.78° E, which correspond to the main frontal thrusts of the SE Carpathians and Subcarpathians nappes (**Fig. 3**). In latitude, distribution is less conclusive as the two lineaments previously mentioned are segmented in four groups – two specific to the Tarcăunappe

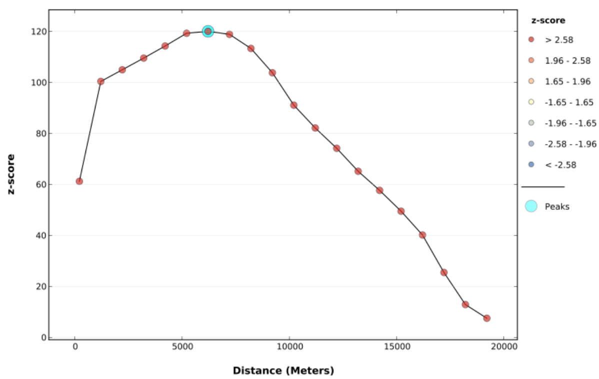


Fig. 4 Spatial autocorrelation of k_{sn} values by distance.

(45.65° – 45.7° N and 45.98° – 46° N), one to the Marginal Folds (45.87° – 45.95° N) and the last one to all three nappes (45.78° - 45.8° N). This correlation can be the effect of a differential uplift which also imposed the characteristics of the present drainage network.

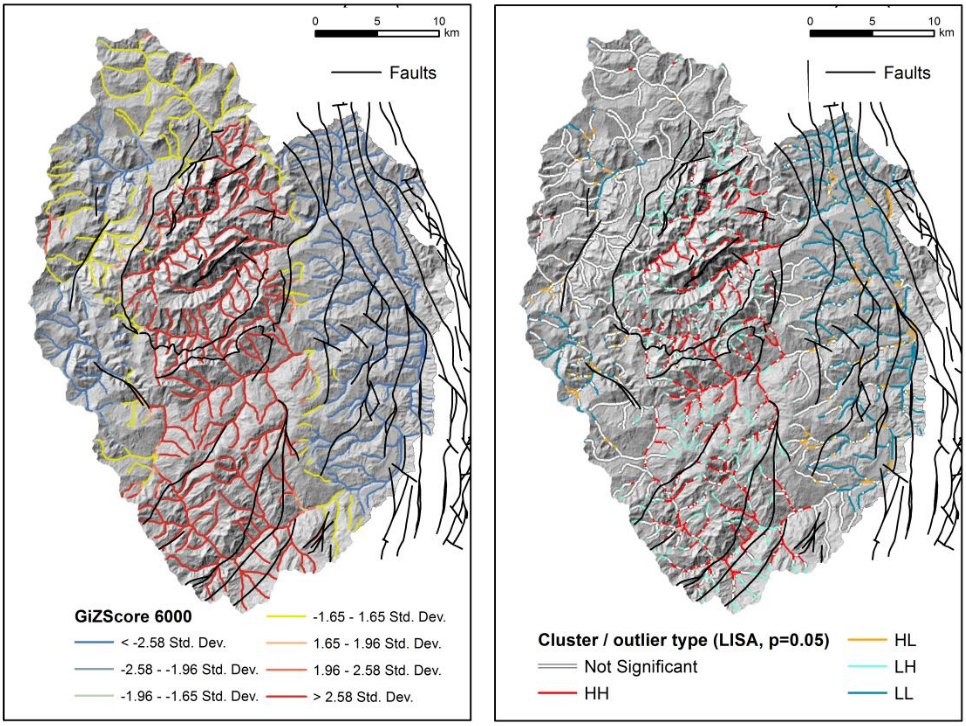


Fig. 5 GetisOrd* statistic estimation for the k_{sn} values and LISA –generated cluster/outlier types: cluster of high values (HH), cluster of low values (LL), outlier in which a high value is surrounded primarily by low values (HL) and outlier in which a low value is surrounded primarily by high values (LH).

In order to quantitatively asses the observed pattern in values we have tested the spatial autocorrelation of the data using LISA (Anselin's Local Moran's I) and GetisOrdGi* statistics. Because of the local character of the computations a fixed distance of 6 km band has been used to define the neighbors included in the analysis. This exhibits the maximum clustering (in terms of Z score) and was determined by measuring the spatial autocorrelation at multiple scales (**Fig. 4**).

GetisOrdGi* statistic estimated for the normalized steepness index indicates a clear cluster of high values occurring in the central part of the catchment, equally in the Tarcau nappe and Marginal Folds domains (**Fig. 5**). At a 95% confidence interval, most of the stream segments draining this region are steeper than the average despite the specific variability of the flysch rock classes. In the folded structures of the Subcarpathians, with comparatively are lowerk_{sn}, a cluster of low values can be generally identified. However several local digressions from this context (stream segments with high values surrounded by features with low values - HL) are identified by LISA and can be roughly correlated with the existing fault system.

5. CONCLUSIONS

Spatial analysis of the over steepened stream segments in the upper catchment of Putna River indicates that the geographic clustering of the values is more significant than the lithological one. Although the rock strength can influence the local stream steepness, this is not sufficient to explain the regional distribution of the values. In this context, recent tectonic evolution of the South-Eastern Carpathians, particularly, the peripheral uplift near the Carpathian and Subcarpathian thrust fronts, had more influence. The largest concentration of steep channel reaches, in terms of magnitude and frequency, mostly coincides with the exposure of the Cretaceous sediments, in the center of the Vrancea half-window. According to Necea (2010) this exposure was the result of a major uplift event (3,2±0,3 mm y^{-1}) in the Early Pleistocene.

Use of spatial autocorrelation techniques in the assessment of the tectonic signals at regional scale improved the analysis of k_{sn}values. However at local scale the influences of lithology or more random mass wasting processes on the channel steepness can be more important but harder to evaluate using a cluster analysis.

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REFERENCES

Anselin, L. (1995) Local Indicators of Spatial Association – LISA, *Geographical Analysis*, 27(2), 93–115.

Bertotti G., Maţenco, L. &Cloetingh, S. (2003) Vertical movements in and around the SE Carpathian foredeep: Lithospheric memory and stress field control, *Terra Nova*, 15, 299-305.

Burbank, D.W. & Anderson, R.S. (2001) *Tectonic Geomorphology*, Blackwell Scientific, Oxford.

Cloetingh, S., Maţenco, L., Bada, G., Dinu, C. &Mocanu, V. (2005) The evolution of the Carpathians-Pannonian system: Interaction between neotectonics, deep structure, polyphase orogeny and sedimentary basins in a source to sink natural laboratory.*Tectonophysics*, 410 (1-4), 1-14.

Duvall, A., Kirby, E. & Burbank, D. (2004) Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California.*Journal of Geophysical Research*, 109, F03002.

Fielitz, W. &Seghedi, I. (2005) Late Miocene - Quaternary volcanism, tectonics and drainage system evolution in the East Carpathians, Romania.*Tectonophysics*, 410, 111-13.

Flint, J.J. (1974) Stream gradient as a function of order, magnitude, and discharge.*Water Resources Research*, 10, 969–973.

Gupta, S. (1993) Drainage deflection by actively growing anticlines at the Himalayan mountain front: Implications for Himalayan drainage patterns. In: Yu, B., Fielding, C.R. (Eds.), Modern and Ancient Rivers: Their Importance to Mankind,*Fifth International Conference on Fluvial Sedimentology, Conference Proceedings,* Keynote Addresses, and Abstracts, Brisbane, 47.

Hack, J. (1957) Studies of Longitudinal Stream Profiles in Virginia and Maryland.*Geological Survey Professional Paper,* 294 – B, 45- 95.

Hack, J.T. (1973) Stream-profile analysis and stream-gradient index.*Journal of Research of the U.S. Geological Survey,* 1, 421–429.

Holbrook, J. M. &Schumm, S.A. (1999) Geomorphic and sedimentary response of rivers to tectonic deformation: A brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings, în Special issue on Tectonics of Continental Interiors.*Tectonophysics*, 305, 287-306.

Ichim, I., Rădoane, M., Rădoane, N., Grasu, C. &Miclăuş, C. (1998) *Sediment dynamics*. *Application to Putna River – Vrancea* (in Romanian), Edituratehnica, Bucharest.

Kirby, E. & Whipple, K. (2001) Quantifying differential rock-uplift rates via stream profile analysis.*Geology*, May 2001, 415-418.

Kirby, E. & Whipple, K. (2003) Distribution of active rock uplift along the eastern margin of the Tibetan Plateau: Inferences from bedrock channel longitudinal profiles.*Journal of Geophysical Research*, 108, v B4.

Lague, D. (2014) The stream power river incision model: evidence, theory and beyond.*Earth Surf. Process. Landforms,* 39, 38–61.

Maţenco, L., Bertotti, G., Cloetingh, S. &Dinu, C. (2003) Subsidence analysis and tectonic evolution of the external Carpathian-Moesian Platform region during Neogene times.*Sedimentary Geology*, 156(1-4), 71-94.

Maţenco, L., Bertotti, G., Leever, K., Cloetingh, S., Schmid, S., Tărăpoancă, M. &Dinu, C. (2007) Large-scale deformation in a locked collisional boundary: Interplay between subsidence and uplift, intraplate stress, and inherited lithospheric structure in the late stage of the SE Carpathians evolution.*Tectonics*, 26(4).

Merten, S. (2011) *Thermo-tectonic evolution of a convergent orogen with low topographic build-up*. Exhumation and kinematic patterns in the Romanian Carpathians derived from thermochronology, VrijeUniversiteit, Amsterdam.

Necea, D., (2010) *High-resolution morpho-tectonic profiling across an orogen: tectonic-controlled geomorphology and multiple dating approach in the SE Carpathian*, VrijeUniversiteit, Amsterdam.

Necea, D., Fielitz, W. &Maţenco, L. (2005) Late Pliocene Quaternary tectonics in the frontal part of the SE Carpathians: Insights from tectonic geomorphology.*Tectonophysics*, 410(1-4), 137-156.

Ord, J. K. &Getis, A. (1995) Local spatial autocorrelation statistics: distributional issues and an application. *Geogr. Anal*. 27 (4), 286–306.

Rădoane, M., Rădoane, N. &Dumitriu D. (2003) Geomorphological evolution of longitudinal river profiles in the Carpathians. *Geomorphology*, 50(4), 293–306.

Snyder, N., Whipple, K., Tucker, G. &Merritts, D. (2000) Landscape response to tectonic forcing: DEM analysis of stream profiles in the Mendocino triple junction region, northern California.*Geological Society of America Bulletin*, 112 (8), 1250-1263.

Tărăpoancă, M., Bertotti, G., Maţenco, L., Dinu, C. &Cloetingh, S. (2003) Architecture of the Focsani depression: A 13 km deep basin in the Carpathians bend zone (Romania).*Tectonics*, 22(6), 1 – 17.

Van der Hoeven, A.G.A., Mocanu, V., Spakman, W., Nutto, M., Nuckelt, L., Maţenco, L., Munteanu, L., Marcu, C. &Ambrosius B.A.C. (2005) Observation of Present-day Tectonic Motions in the South-Eastern Carpathians: Geodetic Results of the ISES/CRC-461 GPS Measurements.*Earth Planett. Sci. Lett*, 239, 177-184.

Vanlaningham, S., Meigs, A. &Goldfinger, C. (2006) The effects of rock uplift and rockresistance on river morphology in a subduction zone forearc. *Earth Surface Processes and Landforms*, 31, 1257-1279.

Whipple, K., Wobus, C., Crosby, B., Kirby, E. &Sheenan, D. (2007) New tools for quantitative geomorphology: Extracting and interpretation of stream profiles from digital topographic data.*GSA Annual Meeting*, Boulder, USA.

Wobus, C., Whipple, K., Kirby, E., Snyder, N., Johnson, J., Spyropoulou, K., Crosby, B. &Sheehan, D. (2006) Tectonics from topography: procedures, promise, and pitfalls. In: *Tectonics, climate, and landscape evolution. Special Paper - Geological Society of America*, 398, 55-74.